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## **The Joint Strike Fighter (JSF) PHM and the Autonomic Logistic Concept: Potential Impact on Aging Aircraft Problems**

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### **ABSTRACT:**

The JSF Autonomic Logistics (AL) system is a new supportability concept that will enable the aircraft to be better utilized throughout the life of the platform, and at a lower cost as compared with legacy aircraft. Autonomic Logistics is, simply put, the automation of the logistics environment such that little human intervention is needed to engage the logistics cycle. Actions that will be automated within the JSF supportability concept include maintenance scheduling, flight scheduling, ordering spare parts, and the like. The cornerstone of Autonomic Logistics is an advanced diagnostic and Prognostics and Health Management (PHM) system. The PHM provides the data, information, and knowledge for initiating the AutoLog chain of events. PHM is the ability of the aircraft to do fault detection (FD), fault isolation (FI), and accommodation real-time on-board the aircraft. Along with this FD/FI capability, some of the other facets of PHM include fault prediction on selected components, parts life usage tracking, fault filtering and reporting, and recommended action to the pilot only when action is necessary. It is intended that in most cases, maintenance actions and lifing decisions will be based on the actual material condition of the equipment components. The proposed architecture of this PHM concept includes a hierarchical approach where data begins at the sensor level and is transported up to area reasoners that turns this data into information about a particular subsystem. From the area reasoner, the information is then passed up to a top level Air Vehicle Reasoner where subsystem information is then fused to give knowledge about the health of the entire air vehicle. Additionally, many of the technologies that are being developed for the JSF PHM suite could be applied to legacy aircraft and would show significant benefits in respect to LCC and maintainability issues. In many cases, the capability of PHM sensors and prognostic technologies will enable the ability to "see" incipient faults in subsystem components very early prior to their progressing to final system failure. These capabilities will enable accurate useful life remaining predictions and more aggressive health management of assets. Through very accurate tracking of the life usage data for component parts, the JSF PHM and AL will be able to anticipate many problems that plague current legacy aircraft; giving a lead time to provide fixes before the actual problems become fleet wide and catastrophic. The PHM architecture will directly interface with the Joint Distributed Information System (JDIS), which is the information system that will enable the Autonomic Logistics functions. The JDIS could automatically forward to the Original Equipment Manufacturer (OEM) data on problems that arise within the fleet, thus alerting them to a developing situation sooner, and enabling them to provide faster, cheaper fixes to these problems. With these safeguards in place, the JSF will put itself in a position to not only quickly react to ageing aircraft problems, but to avoid many of them before they happen.

### **BACKGROUND:**

In today's world, as defense budgets continue to shrink, it is becoming increasingly more difficult to maintain a constant level of force structure through new acquisitions. A direct result of these shrinking budgets and decreased purchases is a current fleet of increasingly aging aircraft. We are forced

to use the existing fleet assets much longer than originally projected and more often, in new and unanticipated roles. No longer will mass purchases of many models of new aircraft ensure that there are plenty of assets to meet all operational requirements. Much of today's aircraft fleet is well over 20 years old, which presents a new variety of problems in maintaining those aircraft that are nearing their operational life when there is no immediate sign of a replacement. All too frequently degraded equipment, assisted by inadequate maintenance practices, lead to preventable incidents in which people are injured or killed. This situation also ensures additional and very high operational and support costs; since older systems are less reliable, and harder and more costly to maintain.

A discussion of the Joint Strike Fighter's PHM system will be presented in this paper, with an emphasis on its capabilities and its aims to enhance aircraft safety; significantly reduce operation and support costs; as well as minimize the impacts of the enviable aging fleet. The PHM system is, by design, envisioned to provide an information rich and highly intelligent aircraft. A major tenet of this discussion will be that robust information sources provided by the PHM system can and will be used to mitigate aging aircraft problems.

## MAIN:

### AUTONOMIC LOGISTICS

The JSF program is in a unique position to fully take advantage of modern technologies to significantly reduce operational and support cost as well as to be able to design the air vehicle with these aging aircraft problems in mind. In order to do this, the JSF program has devised a revolutionary new support concept called Autonomic Logistics. The aim and over-arching strategy of Autonomic Logistics is to provide a comprehensive logistic support environment for the JSF by including the following key features:

- A highly reliable and maintainable (R+M) designed intelligent aircraft which encompasses a comprehensive Prognostics and Health Management (PHM) capability to enhance flight safety, improve efficiency of the logistics chain, and allow scheduling of logistic events to compliment operational planning.

- A technologically enabled maintainer who, through the use of innovative and automated tools and technical publications, will be capable of efficiently and effectively maintaining the JSF with less specialized training and more "on the spot" training. This will be accomplished by the use of Interactive Electronic Tech Manuals (IETM's) and will allow the use of fewer maintainers, cross trained over many sub-systems.

- A fully capable Joint Distributed Information System (JDIS) that incorporates advanced information technology to provide decision support tools and an effective communication network linking the JSF with the logistics infrastructure to provide proactive support.

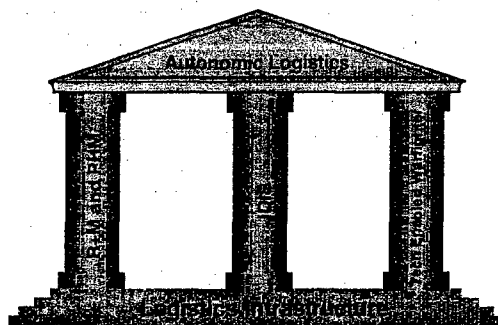
- A logistics infrastructure that is sufficiently responsive to support requirements within a timeframe that allows the JSF weapon system to generate the required number of effective sorties at the least cost.

These four elements of Autonomic Logistics each have a vital role to play in establishing a new paradigm of affordability of the Joint Strike Fighter weapon system for the 21<sup>st</sup> century. This paper discusses these elements and how they will be used to mitigate the problems associated with an aging aircraft fleet. Figure 1 shows a notional for how these four elements come together to "hold up" the overall view of Autonomic Logistics.



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## Key Elements of JSF Autonomic Logistics



Affordable, Survivable, Maintainable, Supportable

**Operationally Available and Lethal**

Figure 1 Autonomic Logistics Concept

### PROGNOSTICS AND HEALTH MANAGEMENT

The Joint Strike Fighter PHM concept is the cornerstone of Autonomic Logistics. The system incorporates not only an integrated and comprehensive diagnostics system, but also prognostics, and an inclusive information system that utilizes decision support tools for the users. The key underlying theme of the JSF's PHM system is a minimal number of specialized sensors to be used in conjunction with an "area manager" architecture. These area managers contain software reasoners, or software modules in which data from various sources is fused together through means such as fuzzy logic, data fusion, neural nets, model based and case based reasoning and the like in search of anomalies or trends which may indicate defective or faulty parts. The idea is not to overload the aircraft with an abundant amount of sensors which tend to fail and induce an added ambiguity when attempting to isolate faults and failures, but to utilize as many already present aircraft parameters as possible with assistance coming from various strategically placed sensors.

Each area manager continually monitors a particular subsystem of the aircraft. Thus we have area managers for propulsion, structures, utilities & subsystems, vehicle management system, and mission systems. Having its own computing capability and software algorithms, the Area Manager automatically analyzes the signals from the sensors and other data sources to determine whether the devices or components of the given subsystem are behaving properly, or are exhibiting characteristics which may lead to failure. The JSF software architecture is constructed to minimize ambiguities. All of the subsystem area managers provide their output to a single air vehicle manager for further fusion of information across the air vehicle and elimination of ambiguities. This information is then filtered to send to the pilot only that information which he can use and act on, and the rest is conveyed to maintenance personnel for action (figure 2). The purpose of this software architecture is twofold: first, it allows the diagnostic system to perform more functions without the introduction of an abundant amount of specialized sensors. On today's digital aircraft, there is already an enormous amount of data present on flight data recorders and MUX busses. It is the job of the software architecture to turn this data into actual information that can then be used in the maintenance of the aircraft. Second, by fusing data from various sources, anomalies can be cross-checked with information from other subsystems in order to corroborate or dispute a potential alarm. With this concept, no longer will alarms be triggered based upon the input of a single sensor. All sensor



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### PHM Architecture

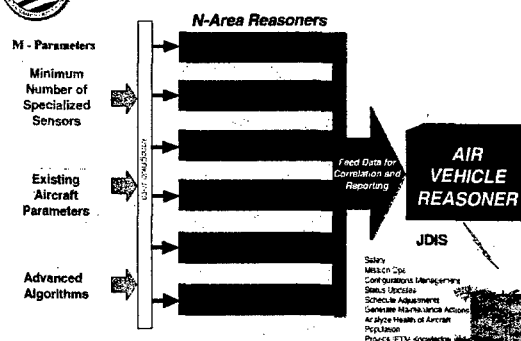


Figure 2: JSF PHM Architecture

data will be validated in the Area Managers and Air Vehicle Manager with other sensor data or aircraft parameters in order to verify the fault. Data filtering will be accomplished with new technology employing coherence analysis that detects component performance deviations from normal. Other non-critical information will be digitally stored for downloading upon landing.

Another aspect of PHM is to perform many of the prognostic calculations, remaining useful life calculations, cycle counting, and lifeing of components. This processed information, along with the rest of the information taken from the air vehicle is then passed along to the JDIS to inform the supply chain what it has to do to keep the airplane operationally effective. This is where many of the benefits will be realized. Prognostics, the way the JSF plans to implement it, has one overarching objective: to ensure that there are no surprises when maintaining the aircraft. Prognostics will occur across the air vehicle, just like the diagnostic system. From flight control systems to rotating machinery in the engine, work is ongoing to attempt to predict the life of all mission and flight critical parts of the aircraft, as well as the life of any parts where the technical risk and benefits can justify the undertaking. The metric to be used in this undertaking is probability of failure within a specified number of flight hours. For example, it is the goal that the JSF will be able to prognose that a certain hydraulic pump has a 90% chance of failing within the next 10 flight hours. This way, maintenance personnel will be able to make intelligent, informed decisions regarding the removal and replacement of parts. Another aim of the JSF prognostics system is to have an estimate of remaining useful life of a component at any given time that the component is on board an aircraft. With a new part, this number will most likely be the time set forth in the current RCM method; however, as the component approaches the removal point, prognostic algorithms will adjust the remaining life based upon how that part is being used. For instance, an aircraft structural member would exhibit a much longer useful life if the plane were primarily used for ferry missions as would the same member on an aircraft that was performing a lot of high G maneuvers. The prognostic algorithms will be able to account for this and adjust maintenance schedules accordingly.

Prognostics will allow a lead time for the logistics pipeline to get parts and to train maintainers to change those parts. Also, it will allow for "opportunistic maintenance", or the act of grouping maintenance actions at a single time while an aircraft is already down. For instance, a hypothetical aircraft is down for a routine engine wash. While it is being attended to, the prognostics system informs maintainers that the primary auxiliary power unit (APU) has begun to degrade and will need to be replaced within the next 15 flight hours. It also informs the maintainers that the oil in the engine is beginning to show signs of coking and has an undesirably high content of fragments. Hence, all three maintenance actions can be taken care of with a single downing of the aircraft, vice three separate maintenance actions which would keep the plane out of commission for some time. As an additional benefit, these maintenance actions would keep the APU from failing at a later time, which may have been a very critical time in a mission being flown.

Another aspect of Autonomic Logistics, briefly mentioned above, is part tracking. With Autonomic Logistics, all component parts will be tracked by serial number across all aircraft tail numbers. This will assist in catching potential fleet-wide problems before they become problems. An example would be if the Navy were to switch bearing manufacturers for some reason (cheaper, original manufacturer went out of business, etc.). Suppose new bearings were not performing up to standard, at the first sign of a bad trend, the JDIS would be able to identify all bearings from the given shipment(s) and their locations and pull them before they started failing while in operation. This would avoid having to ground an entire fleet in order to check all bearings on all aircraft to identify the faulty ones.

#### JOINT DISTRIBUTED INFORMATION SYSTEM

The "backbone" of Autonomic Logistics is the Joint Distributed Information System (JDIS), and it works hand in hand with PHM. While the importance of fault prediction, detection, and isolation cannot be over-emphasized, without a means of properly communicating this information, the actual realized benefits can be much less than anticipated. JDIS provides the conduit that takes the prognostic and diagnostic information transmitted by the aircraft and determines from it the manpower numbers, capabilities and training requirements to complete the necessary tasks. Some tasks that will be automatically performed through and/or integrated with JDIS are: mission planning, maintenance action scheduling, ordering of spare parts, scheduling of flight and maintenance training, assignment of specific pilots to specific missions based upon experience and readiness, assigning specific aircraft to specific

missions based upon aircraft availability and capability, and storing maintenance, training, spare part, and logistic information in the data warehouse. It is important to note here that while all of these tasks will be done automatically, at any given time a person with the necessary authority can access the system and make changes as required. By having this requirement, JSF personnel will not have to live with poor decisions that were made because of programming "glitches" or lack of foresight of the programmers.

The information fusion capability of the PHM system will allow JDIS to output and pass on actions and recommendations rather than just data. These decision support tools will include: maintenance information, supply chain management information, health and usage information, training management, and recommendations regarding best use of resources. JDIS will provide the "backbone" information distribution system to integrate PHM supplied data and information with all the other necessary maintenance management, logistics, supply, OEM, mission planning, etc., data bases required to ensure the most fully informed decision process possible. Figure 3 depicts an envisioned example of JDIS functionality.

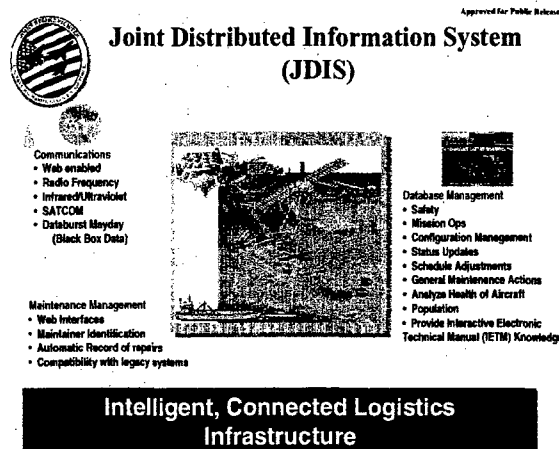


Figure 3 JDIS Functions

#### TECHNOLOGICALLY ENABLED MAINTAINER

The maintainer in the Autonomic Logistics concept has the full set of modern, technologically capable and appropriate tools at his immediate disposal to enable him to prepare the aircraft for its next and subsequent sorties in the most cost effective and timely manner. Coupled with a truly "World Class" and modern Training Environment, the maintenance technician's capabilities will be greatly enhanced by taking advantage of new technology. Some of this new technology will enable truly Interactive Electronic Technical Manuals (IETM's), the Electronic Classroom, Training Continuum/Mission Rehearsal, Embedded Simulation, Virtual Reality feedback tools, On-line Support, etc. The tool sets include: comprehensive knowledge of the actual aircraft health before beginning work (PHM and JDIS), appropriate and timely training to conduct the task (Prognostics lead time, prior training methods), all the necessary material on hand before commencement of work (Prognostics lead time), and interactive guidance available in real time to provide supplementary information as required. The connectivity of the maintainer to the aircraft systems and maintenance management provides the response times necessary to conduct maintenance actions without compromising sortie generation requirements.

It is important to note, however, that the logistics and PHM systems require minimal intervention from the maintainer. The ongoing activities within Autonomic Logistics and PHM should be as transparent as possible to the maintainer due to its automatic nature. Tasks are presented to the maintainer in a manner that provides proper procedures, safety, detail appropriate to skill level, rehearsal/review of the task when requested, tools and parts required and quality assurance. The maintenance management environment must aim to monitor, schedule, and prioritize all maintenance activity (on-condition and scheduled) based upon the data provided by PHM and JDIS. There will be less emphasis on diagnostic skills as a result of the highly capable PHM system being incorporated, but the maintainer must be trained in the proper functional utilization of the Autonomic Logistics environment. A full and comprehensive understanding of the

Autonomic Logistics and PHM systems is critical for the maintainer to develop the confidence in the tools that will dictate maintenance tasks, procedures and the training required.

#### ADVANCED LOGISTICS INFRASTRUCTURE

The potential advantages embodied in a substantial PHM capability, a technologically enabled maintainer, and a highly capable JDIS, producing accurate and comprehensive logistics information are all of no avail if the logistics infrastructure is not flexible and responsive enough to generate the necessary support in the right place when required. Equally, the importance of making JSF affordable through its life cycle demands a logistics strategy that explores every means of meeting the support requirements in the most cost effective fashion. Some of the issues to be tackled to have the appropriate infrastructure are as follows:

Levels of Maintenance – In order to minimize the logistics footprint and infrastructure costs, the minimum number of levels of maintenance to successfully meet mission requirements are envisioned.

Inventory Policies – Large quantities of spares carry substantial storage overheads, tie up capital and decrease flexibility within a supply chain management system. Just in time inventory becomes more realistic with this type of data sharing and prognostic capability.

Supply Chain Management – Greater contractor responsibility for logistics system effectiveness is likely to require less government intervention in supply chain management. The JSF supply chain will have to interface seamlessly with existing logistics chains for common items at the Front Line. Embarked, forward deployed, and on-base retail supply activities will most likely continue to be conducted by the Services.

These factors, along with a host of other factors will help to realize the potential benefits of Autonomic Logistics. While not directly attributable to reducing traditional aging aircraft problems, an advanced logistics infrastructure plays a role in realizing all of the benefits mentioned above, and thus provides an integral part of Autonomic Logistics.

#### APPLICABILITY TO AGING AIRCRAFT PROBLEMS :

Aircraft begin to age immediately after they are manufactured and introduced into fleet operations. The JSF PHM system and Autonomic Logistics concept, by vision and design, will provide levels of safety, maintainability, supportability, and affordability never achieved before. Many of the capabilities and benefits provided by this concept and these systems will significantly mitigate and/or avoid many typical aging aircraft problems as the JSF ages. While the PHM system and the Autonomic Logistics concept are being designed and integrated from the ground up with the "brand new" JSF aircraft program; many their specific capabilities could also benefit older legacy platforms on a case-by-case basis.

With today's troubleshooting methods of aircraft failures, there are many cases in which aircraft parts are replaced and sent to the depot level where they are found to "retest ok" (RTOK). Many times, these parts that have been removed and tested ok find their way back to the flight line only to be re-installed into another aircraft. In these cases, the part may or may not be faulty; however, this adds a fairly large measure of uncertainty as to the ability of that part to perform its function. As aircraft platforms age, the number of these "uncertain" parts being used increases due to the need to re-use them because of the inability to order more (supplier may have gone out of business, too costly to order in small quantities, lead time to order too long, etc...). To further complicate this matter, over periods of time, these parts naturally tend to accumulate in the supply chain, thus making a clear distinction between good and bad parts somewhat uncertain. Implementing the PHM system as described above would lead to a much greater fault isolation rate and, consequently, fewer removals of good parts. This would lead to fewer (ideally zero) RTOK cases and, hence, zero bad parts in the supply chain.

The Prognostics capability of Autonomic Logistics will play a large part to improving the sortie generation rate of an aircraft and promote safety at the same time for aging aircraft. The additional lead time for maintenance actions will prove invaluable, not just in the latter stages of the aircraft's life cycle, but in all stages of the life cycle. As aircraft age, the number of parts reaching the end of their useful life will increase. This lead time will provide a valuable means of managing this natural turnover. By having this capability, the JSF will be kept at mission ready status over the life cycle with minimum amount of unscheduled grounded aircraft to reduce sortie generation capability.

Additionally, with the lead time notice to order more parts, ideally there would be no more cannibalization of aircraft. Many squadrons have what is known as a "hanger queen", or an aircraft that is in the hanger for the purpose of donating needed parts to operational aircraft. This presents a much faster solution than downing multiple aircraft while awaiting shipments, however it depletes the force structure of the squadron.

The Joint Distributed Information System also plays a key role in mitigating aging aircraft problems. By being able to automatically perform many of the JDIS functions, re-planning squadron and fleet operations will not be as difficult as previous, and what were once "severe" problems will be mitigated to minor inconveniences. For example, a hypothetical situation where a flight schedule has been planned out for a particular day during war time operations may turn disastrous when it is discovered that there is a defective load of control surface actuators that were shipped from the vendor. These actuators would effectively render useless all control surfaces that were being commanded by this shipment, thus would lead to loss of aircraft. In a legacy fleet, the entire wing would be grounded until the malfunctioning parts could be accounted for and replaced with good parts. Afterwards, a new flight schedule would have to be developed if time permitted to complete the missions. In the JSF world, a quick search of JDIS would lead to an immediate knowledge of the locations of the actuators and the aircraft they are housed on. The JDIS could then re-plan the flight operations with the new information of which aircraft were no longer functional, and operations would continue as normal if appropriate numbers of aircraft were unaffected, or on a limited basis as aircraft became available.

This situation could be easily modified to claim that the load of actuators were not defective, but had begun to reach the end of their useful life and were failing at an unusually high rate. In this case, the trend would have been noticed well in advance, and all actuators would have been effectively changed prior to the specific day in question. Again, a quick scan of JDIS would reveal the locations of the malfunctioning parts and those specific aircraft could be grounded at times that would convenience the flight schedule, thus achieving virtually no visible effects throughout the squadron.

Another way in which JDIS can mitigate many of the problems of aging aircraft is by keeping accurate maintenance records. If a particular part is succumbing to a particular failure mode, it may not be visible at the lowest wing or squadron level. But, as JDIS correlates this data across many wings and squadrons, it could possible "see" that the part is having trouble, thus prompting vendors to make design changes on the part to alleviate the problem.

The parts life tracking feature of the Autonomic Logistics system will also help to mitigate aging aircraft problems. By tracking parts and their actual life expended, fleet users will be aware of the actual condition of their assets and will gain an increased awareness as to their readiness. This awareness will translate to an increased confidence in the force structure and subsequently reduce the numbers of downed aircraft later in the life cycle that are undergoing preventative maintenance.

Additionally, the JSF is being designed with an open architecture system to make future unforeseen problems easier to cope with by facilitating the integration of technological fixes to the air vehicle. This is particularly true regarding future software changes and updates. This is being done by separating the Operational Maintenance Profile (OMP) from the Operational Flight Profile (OFP) software programs. This makes updating all PHM and JDIS related software not subject to the rigorous flight qualifications as the flight related software. This approach should enable new and unanticipated future problems to be addressed quickly and affordably. It is the goal of the JSF Autonomic Logistics concept to not only facilitate all maintenance actions and logistics functions, but to avoid the problems that traditionally occur in the aircraft regime, and the JSF Program Office feels that, with the proposed system, this will happen.

## SUMMARY

All elements of Autonomic Logistics are part of a complete system that will manage JSF unit deployment and redeployment to ensure proper logistics support. A near-constant monitoring capability that ensures JSF units will be able to support the commander's intent will also become a reality with AL. This support system is designed to make the JSF air vehicle inherently safer to operate, much easier to



maintain, more affordable to support, and much less problematic than legacy aircraft. Early in the JSF program much analysis was accomplished to provide an excellent understanding of legacy systems and the problems they are encountering. Many initiatives were undertaken to counter these problems in the design concept. The Autonomic Logistic concept and the PHM system embody the results of many of these initiatives, along with newly available technologies and supportability paradigm shifts.

As a direct result of these design studies, common problems that plague legacy systems will no longer be commonplace, and foresight by all people associated with the JSF program will help to facilitate the solving of any unforeseen problems that will inevitably arise as the fleet ages.

The AL system is, by design, envisioned to provide an information rich and highly intelligent aircraft. The robust information sources and increased knowledge provided by the PHM system can and will be used to mitigate many of the aging aircraft problems we experience today.